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Towards optimal data flow in high-energy physics: achieving determinism and real-time in the Mu3e experiment

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The Mu3e experiment, searching for charged lepton flavor violation in the $\mu^+ \rightarrow e^+e^-e^+$ channel with 2*10ˆ-15 sensitivity in Phase I, is under commissioning at PSI PiE5 beamline. To achieve this, Mu3e, operating with the world's most intense continuous muon beam, must handle multi-terabit-per-second data streams from millions of detector channels. Meeting this challenge requires a triggerless DAQ system that achieves extreme throughput, strict determinism, and zero data loss, known as the "impossible triangle,"which has never been achieved in the history of networking or high-energy physics.

We present an FPGA datapath architecture with enhanced data flow dynamics, designed to sustain line-rate processing while maintaining temporal order. This design directly addresses timestamp bursts caused by recurling particles, which can strike multiple detector layers within nanoseconds and generate clusters of nearly simultaneous events. Such bursts, when handled with conventional round-robin arbitration, lead to timestamp reordering and bufferbloat due to micro-burst traffic. Our approach provides a generic and scalable solution to maintain strict temporal ordering in high-throughput environments, offering a robust path forward for future high-rate experiments, such as Mu3e Phase II.

Our work raises broader questions at the frontier of data acquisition: 1) How can true line-rate, i.e. O(1), sorting and scheduling be achieved in hardware—and extended, perhaps, even to software? 2) Why is determinism, i.e., data arriving with precise timing at designated ports, fundamental for correctness in high-energy physics experiments? 3) Why do data loss and reordering persist despite the absence of throughput bottlenecks? By addressing these challenges, the Mu3e DAQ system aims not only to enable Phase I and Phase II physics goals, but also to inform the wider academic community, bridging high-energy physics and computer networking, in the pursuit of optimal, real-time data flow.

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